Charmless b-hadron decays

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on behalf of the LHCb collaboration

XXXI^{e} Rencontres de
Physique de la Vallée d'Aoste

Overview

1. Introduction
2. Baryonic B decays
   - Observation of the $B_s^0 \to p\bar{\Lambda}K^-$ decay [LHCb-CONF-2016-016]
   - Observation of the $B_{(s)}^0 \to p\bar{p}h^+h'^-$ decays
3. CP violation in b decays
   - Time dependent CP violation in the $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays [LHCb-CONF-2016-018]
   - Evidence for CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ [Nat. Phys. (2017)]
4. Rare B decays
   - Search for the $B_s^0 \to \eta'\phi$ decay [arXiv:1612.08110, Submitted to JHEP]
   - Observation of the $B^0 \to K^+K^-$ decay [Phys. Rev. Lett. 118 (2017) 081801]
5. Conclusions

Charmless Decays

- Can proceed via

  tree $b \to u$

  penguin $b \to s, \quad b \to d$

- Tree, suppressed by V_{ub}, can have similar magnitude to penguins
- Sensitivity to weak phases from tree-penguin interference
- New physics can appear in loops
- Provide inputs and tests for QCD models

Baryonic *B* decays

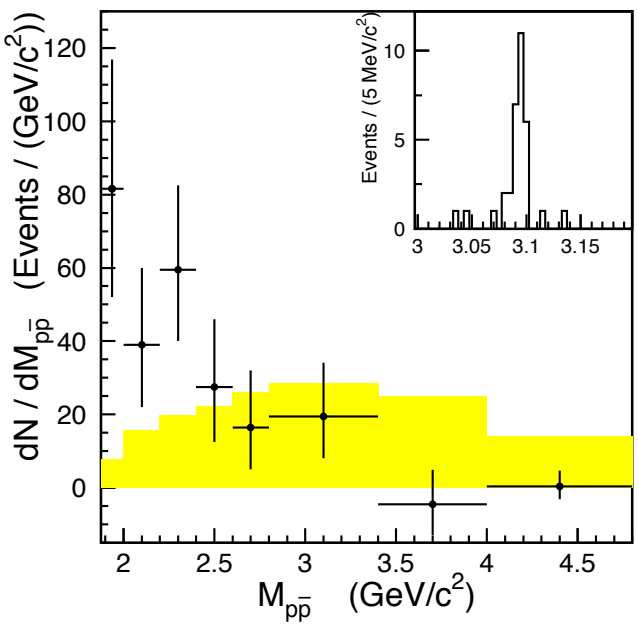
Motivations

- Many baryonic B decays still to be studied / observed
- Multi-body final state tend to have larger BF that 2-body ones

$$\mathcal{B}(B^0 \to \overline{\Lambda}_c^- p\pi^+\pi^-) \sim 10^{-3} \gg \mathcal{B}(B^0 \to \overline{\Lambda}_c^- p\pi^0) \sim 10^{-4}$$
$$\gg \mathcal{B}(B^0 \to \overline{\Lambda}_c^- p) \sim 10^{-5}$$
$$\mathcal{B}(B^0 \to p\bar{p}K^0) \sim 10^{-6} \gg \mathcal{B}(B^0 \to p\bar{p}) \sim 10^{-8}$$

- Threshold enhancement in baryon-antibaryon systems observed in many decay modes (see eg. [Eur. Phys. J. C74 (2014) 3026])

Threshold enhancement observed for the first time by Belle in $B^\pm \to p\bar{p}K^\pm$ [Phys. Rev. Lett. 88 (2002) 181803]



Short history

B factories

- 2002: First observation of a baryonic B decay [Phys. Rev. Lett. 88 (2002) 181803]
- Observation and study of many B^0 and B^+ baryonic decays, both with charm in the final state and charmless
- Observed threshold enhancement in baryon-antibaryon invariant mass of several decays

LHCb

- 2013: First observation of 2-body charmless baryonic mode $B^+ \to p\overline{\Lambda}(1520)$ and first evidence of CP violation in a baryonic B decay seen in $B^+ \to p\bar{p}K^+$ [Phys. Rev. Lett. 113, 141801 (2014)]
- 2013: First evidence of the very suppressed $B^0 \to p\bar{p}$ [J. High Energy Phys. 10 (2013) 005]
- 2014: First observation of a baryonic B_c^+ decay ($B_c^+ \to J/\psi\, p\bar{p}\pi^+$) [Phys. Rev. Lett. 113, 152003 (2014)]

Observation of the $B_s^0 \to p\bar{\Lambda}K^-$ decay

[LHCb-CONF-2016-016]

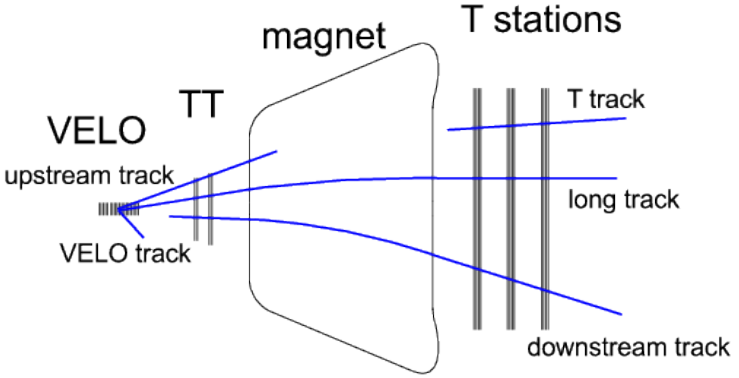
Analysis strategy

[LHCb-CONF-2016-016]

- Goal: Observe first B_s^0 baryonic decay
  - Look for three-body decay as larger BF expected than 2-body
- Signal: $B_s^0 \to p\bar{\Lambda}K^-$
- Normalisation mode: $B^0 \to p\bar{\Lambda}\pi^-$

$$\frac{\mathcal{B}_{\rm sgn}}{\mathcal{B}_{\rm norm}} = \frac{f_d}{f_s}\frac{\mathcal{N}_{\rm sgn}}{\mathcal{N}_{\rm norm}}\frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sgn}}$$

- Dataset: LHCb Run I dataset (3 fb^{-1}), divided per year and reconstruction category
- Selection: neural network against combinatorial background, particle identification criteria on charged hadrons

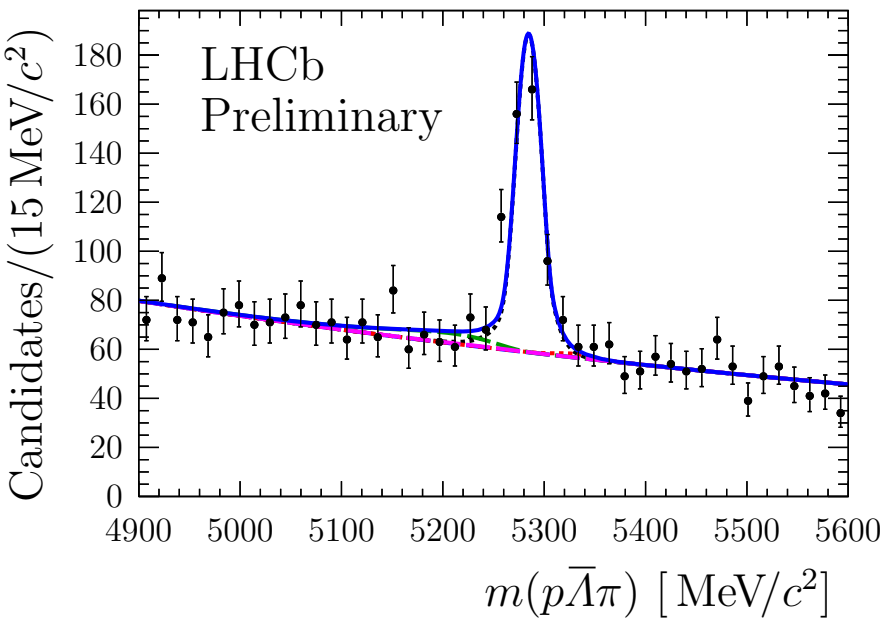


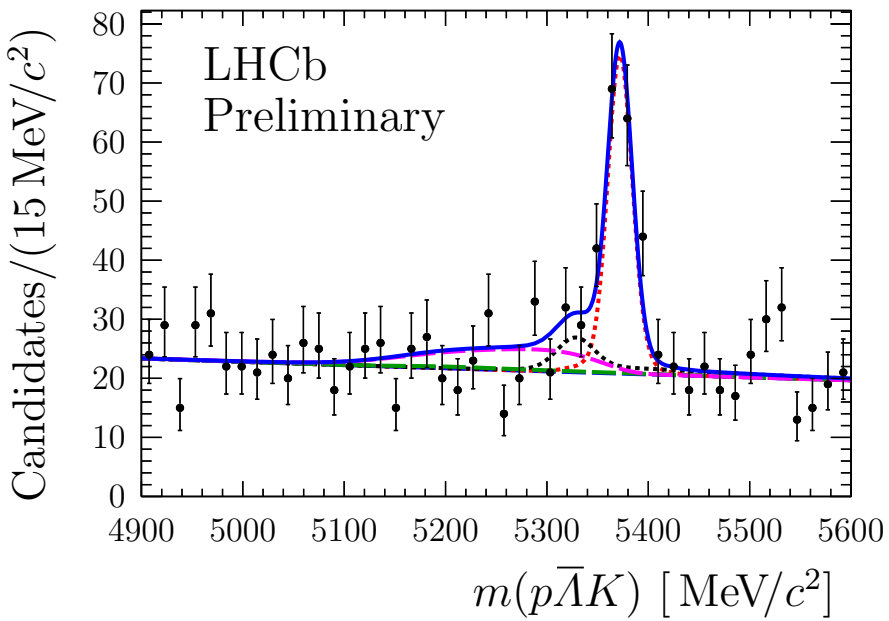
[JINST 10 (2015) P02007]

Fit

[LHCb-CONF-2016-016]

- Perform a simultaneous fit to signal ($B_s^0 \to p\bar{\Lambda}K^-$) and normalisation mode ($B^0 \to p\bar{\Lambda}\pi^-$) for all categories
  - Share shape parameters
  - Constrain cross-feed background from different final states
- Backgrounds considered: combinatorial, $B_s^0 \to p\bar{\Sigma}K^-$, $B^0 \to p\bar{\Sigma}\pi^-$





- Observe $B_s^0 \to p\bar{\Lambda}K^-$ with statistical significance $> 15\sigma$ (260 ± 21 signal candidates from the fit to all the categories)

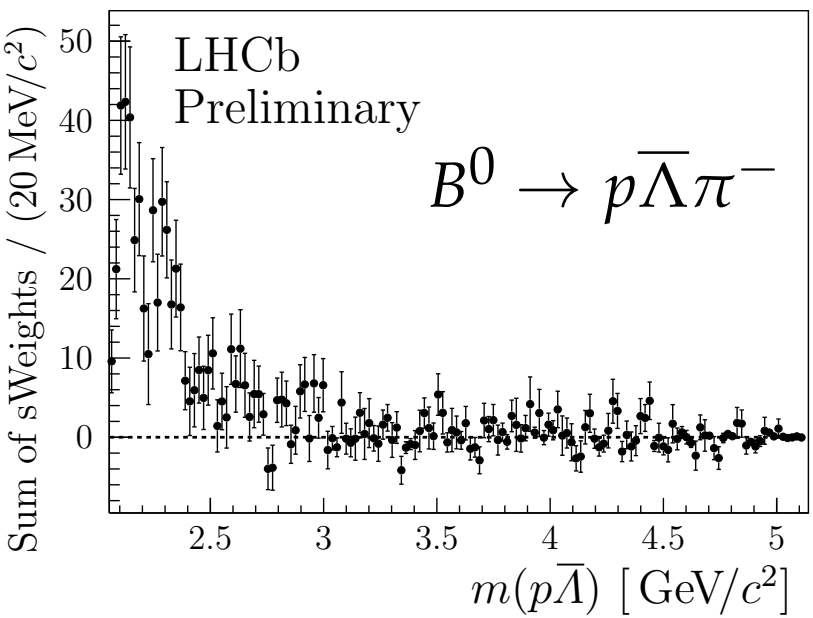
Results

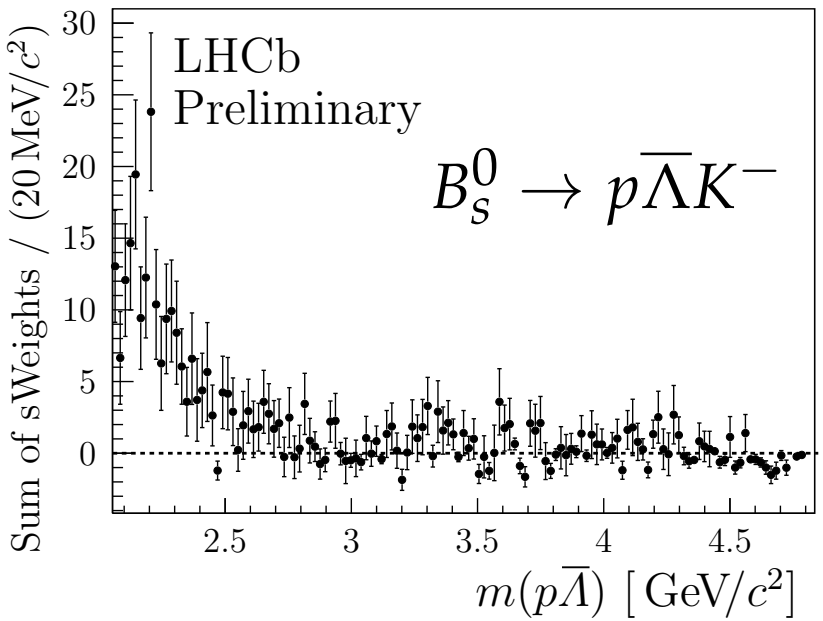
[LHCb-CONF-2016-016]

- First observation of a baryonic B_s^0 decay!
- Branching fraction measured to be

$$\mathcal{B}(B_s^0 + \bar{B}_s^0 \to p\overline{\Lambda}K^-) = [\,5.48^{+0.82}_{-0.80}(\text{stat}) \pm 0.60(\text{syst}) \pm 0.51(\mathcal{B}_{\text{norm}}) \pm 0.32(f_s/f_d)] \times 10^{-6}$$

- Observed threshold enhancement in $p\bar{p}$ mass spectra (backgorund subtracted)





Observation of the $B^0_{(s)} \to p\bar{p}h^+h'^-$ decays

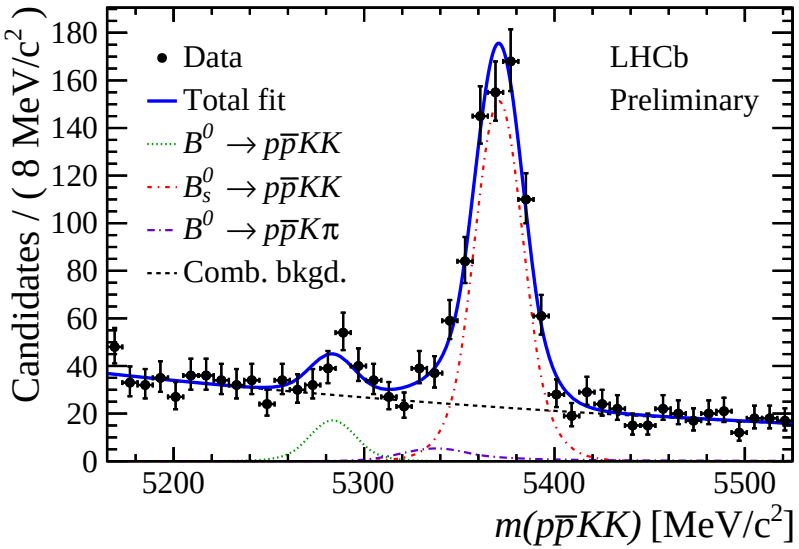
[LHCb-PAPER-2017-005, In preparation]

New

Analysis strategy [LHCb-PAPER-2017-005, In preparation]

- Goal: Observe and measure BF of charmless $B^0_{(s)} \to p\bar{p}h^+h'^-$ modes
  - Only known $\mathcal{B}(B^0 \to p\bar{p}K^{*0}) = (1.24^{+0.28}_{-0.25}) \times 10^{-6}$ (BaBar and Belle)
- Signal: $B^0_{(s)} \to p\bar{p}h^+h'^-$ ($h^{(\prime)} = K$ or π)
  - Excluding the charmonium region: $m(p\bar{p}) < 2.85$ GeV
  - Veto D^0 and Λ_c
- Normalisation mode: $B^0 \to (J/\psi \to p\bar{p})(K^{*0} \to K^+\pi^-)$, same selection as signal except charm vetoes
- Dataset: LHCb Run I dataset (3 fb^{-1})
- Selection: BDT against combinatorial background, particle identification on hadrons (each candidate only in one final state sample)
- Simultaneous fit to invariant mass of 3 final states
- 3-D fit in $m(p\bar{p}K^\pm\pi^\mp)$, $m(p\bar{p})$ and $m(K^\pm\pi^\mp)$ for normalisation mode

Simultaneous signal fits [LHCb-PAPER-2017-005, In preparation]

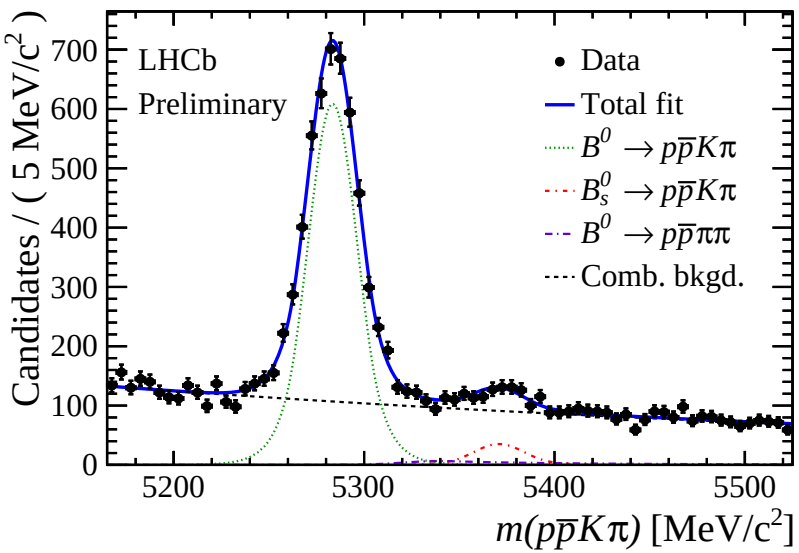


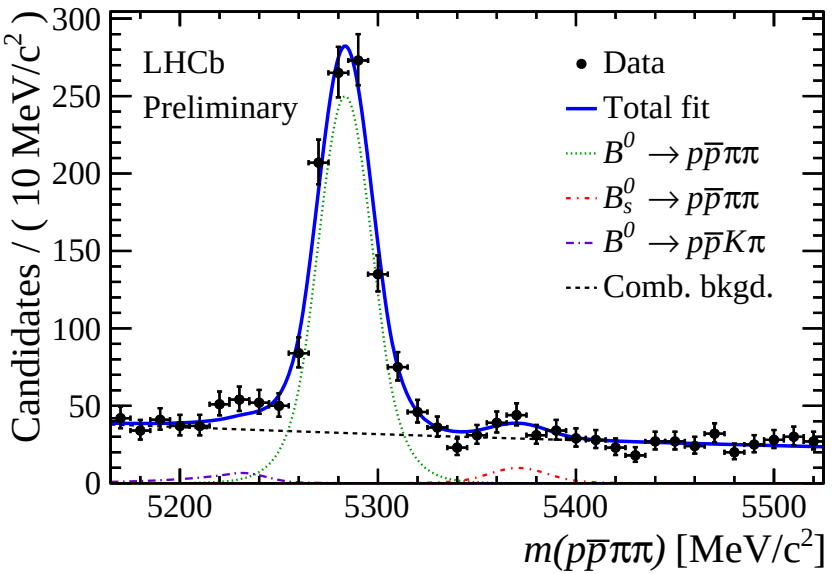
$n_B^{p\bar{p}K^+K^-} = 68 \pm 17$ $n_{B_s}^{p\bar{p}K^+K^-} = 635 \pm 32$

$n_B^{p\bar{p}K^\pm\pi^\mp} = 4155 \pm 83$ $n_{B_s}^{p\bar{p}K^\pm\pi^\mp} = 246 \pm 39$

$n_B^{p\bar{p}\pi^+\pi^-} = 902 \pm 35$ $n_{B_s}^{p\bar{p}\pi^+\pi^-} = 39 \pm 16$

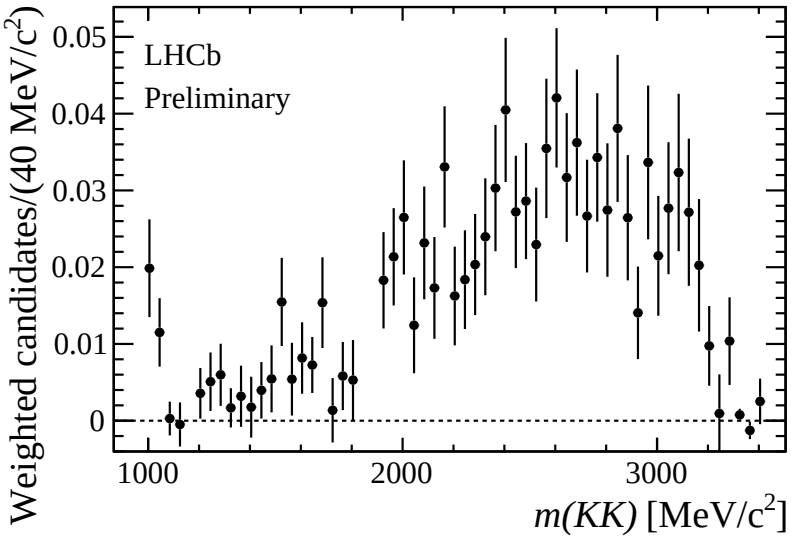
First strong evidence First observations





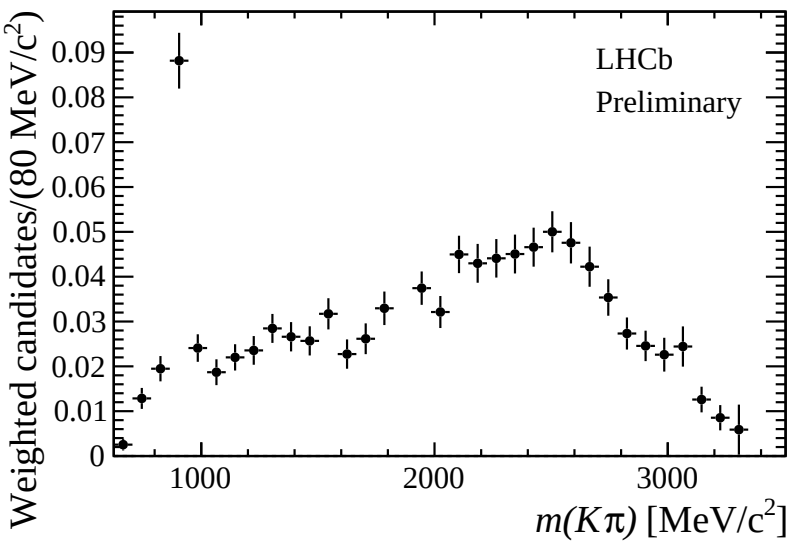
Substructures in $m(h^+h'^-)$ [LHCb-PAPER-2017-005, In preparation]

$B_s^0 \to p\bar{p}K^+K^-$

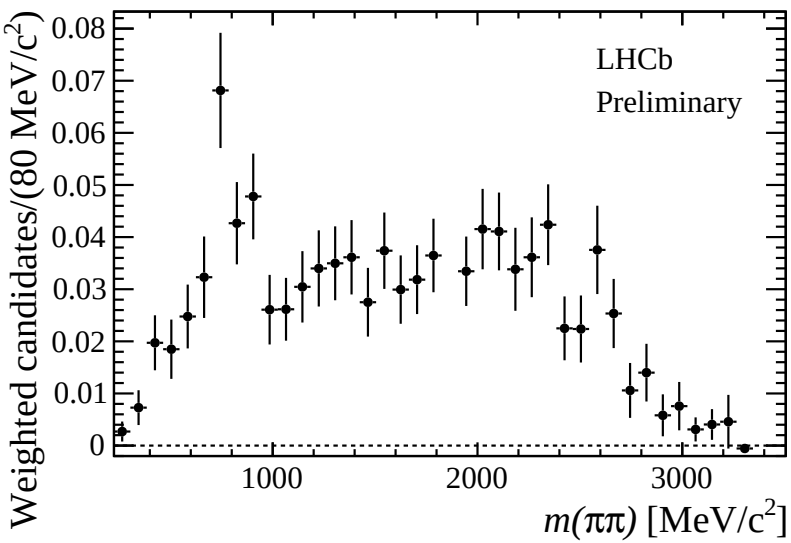


- Efficiency-corrected and background-subtracted
- Vector mesons visible ($\phi(1020)$, $K^*(892)^0$, $\rho^0(770)$)

$B^0 \to p\bar{p}K^\pm\pi^\mp$

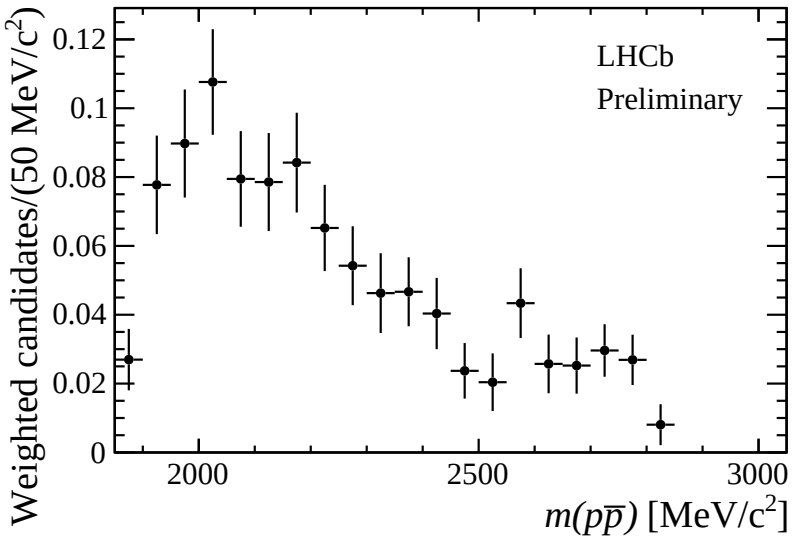


$B^0 \to p\bar{p}\pi^+\pi^-$



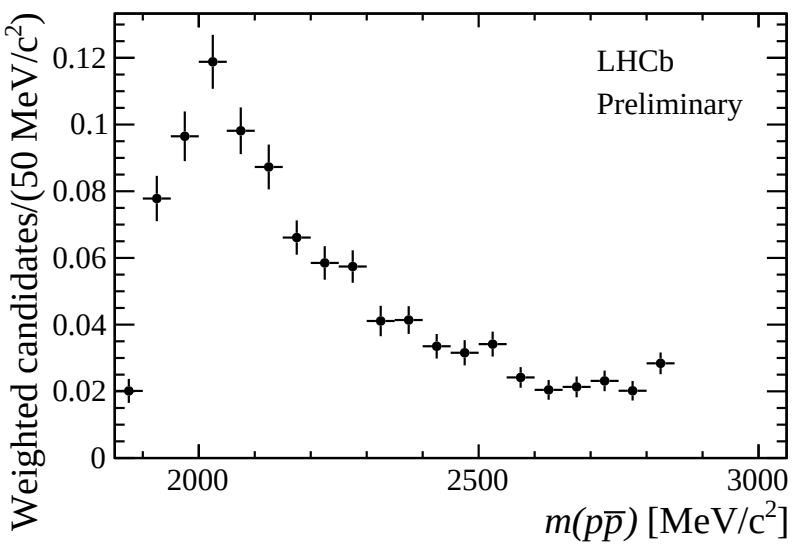
Threshold enhancement in $m(p\bar{p})$ [LHCb-PAPER-2017-005]

$B_s^0 \to p\bar{p}K^+K^-$

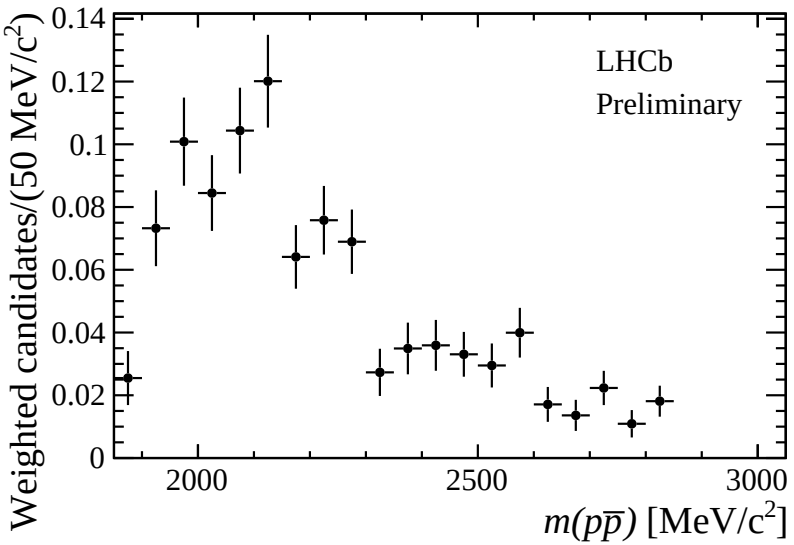


- Efficiency-corrected and background-subtracted
- Clear threshold enhancement

$B^0 \to p\bar{p}K^{\pm}\pi^{\mp}$



$B^0 \to p\bar{p}\pi^+\pi^-$



Results

[LHCb-PAPER-2017-005, In preparation]

- 3 first observations and a strong evidence

Decay channel	Significance [σ]	Branching fraction / 10^{-6}			
$B^0 \to p\bar{p}K^+K^-$	4.1	$0.126 \pm 0.031 \pm 0.013 \pm 0.006$			
$B^0 \to p\bar{p}K^\pm\pi^\mp$	> 25	6.6	± 0.3	± 0.3	± 0.3
$B^0 \to p\bar{p}\pi^+\pi^-$	> 25	3.0	± 0.2	± 0.2	± 0.1
$B_s^0 \to p\bar{p}K^+K^-$	> 25	4.6	± 0.3	± 0.3	± 0.2 ± 0.3
$B_s^0 \to p\bar{p}K^\pm\pi^\mp$	6.5	1.45	± 0.24	± 0.12	± 0.07 ± 0.08
$B_s^0 \to p\bar{p}\pi^+\pi^-$	2.6	0.46	± 0.19	± 0.05	± 0.02 ± 0.03

$$val \pm stat \pm syst \pm \sigma(\mathcal{B}) \pm \sigma(f_s/f_d)$$

- Upper limit set on $\mathcal{B}(B_s^0 \to p\bar{p}\pi^+\pi^-)$

$$\mathcal{B}(B_s^0 \to p\bar{p}\pi^+\pi^-) < 7.3 \times 10^{-7} \text{ at } 90\% \text{ CL}$$

CP violation in *b* decays

Time dependent CP violation in the $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays

[LHCb-CONF-2016-018]

Motivations

[LHCb-CONF-2016-018]

Time dependent asymmetries linked to CPV parameters C_f, S_f and $A_f^{\Delta\Gamma}$

$$\mathcal{A}(t) = \frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right)}$$

$$|C_f|^2 + |S_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1$$

- Rich set of physics processes contributes to $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays (Tree and penguin contributions, neutral B mixing, possible new physics in loops)
- Time dependent CPV sensitive to CKM phases
  - angles γ and β_s measured in [Phys. Lett. B 741 (2015) 1]
- $C_{\pi^+\pi^-}$ and $S_{\pi^+\pi^-}$ well constrained by B-factories and LHCb
- $C_{K^+K^-}$ and $S_{K^+K^-}$ measured only by LHCb using $1\,\text{fb}^{-1}$ (2011) and no measurement for $A^{\Delta\Gamma}_{K^+K^-}$ [JHEP 10 (2013) 183]

Analysis strategy [LHCb-CONF-2016-018]

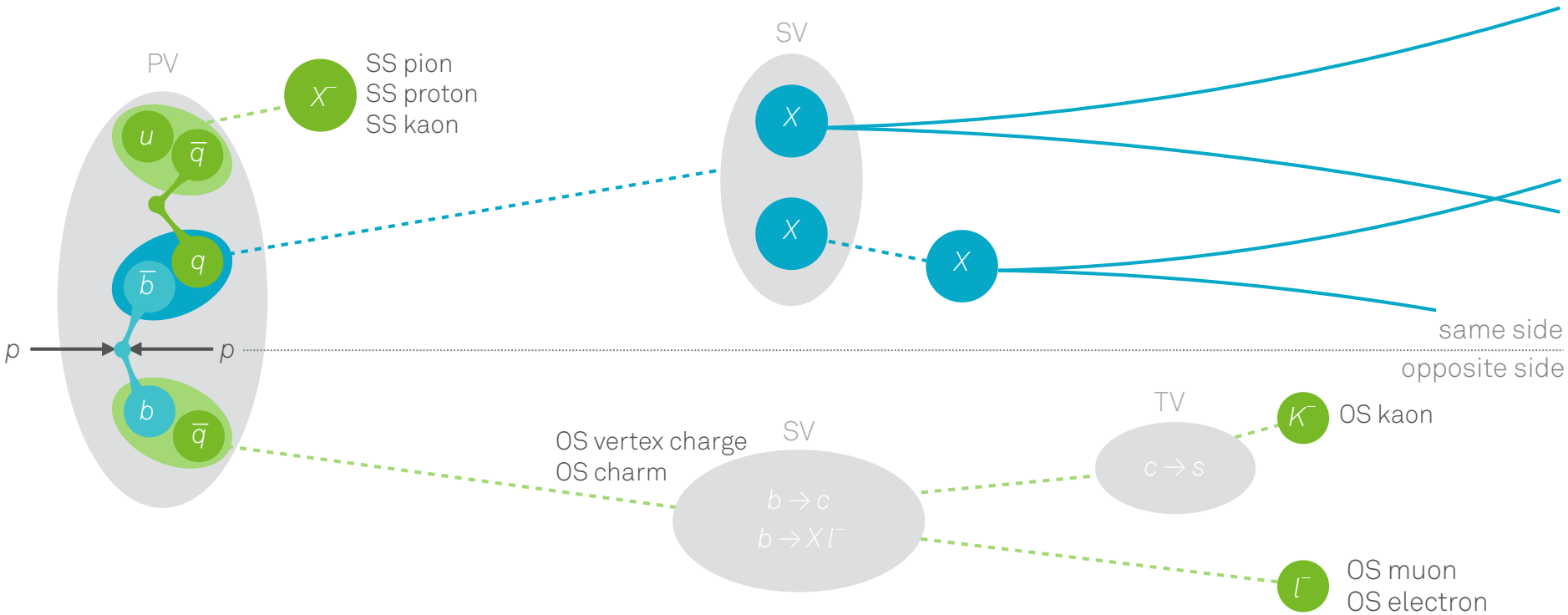
- BDT against combinatorial background, particle identification selection to reduce contamination from other $B \to hh'$ modes to $\sim 10\%$ of the signal.
- CPV coefficients determined from unbinned maximum likelihood fit to
  - Mass, decay time, per-event mistag probability, per-event decay time error
  - Simultaneous fit to $\pi^+\pi^-$, K^+K^- and $K^+\pi^-$ mass spectra
- Production asymmetry determined from $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$

Analysis strategy

[LHCb-CONF-2016-018]

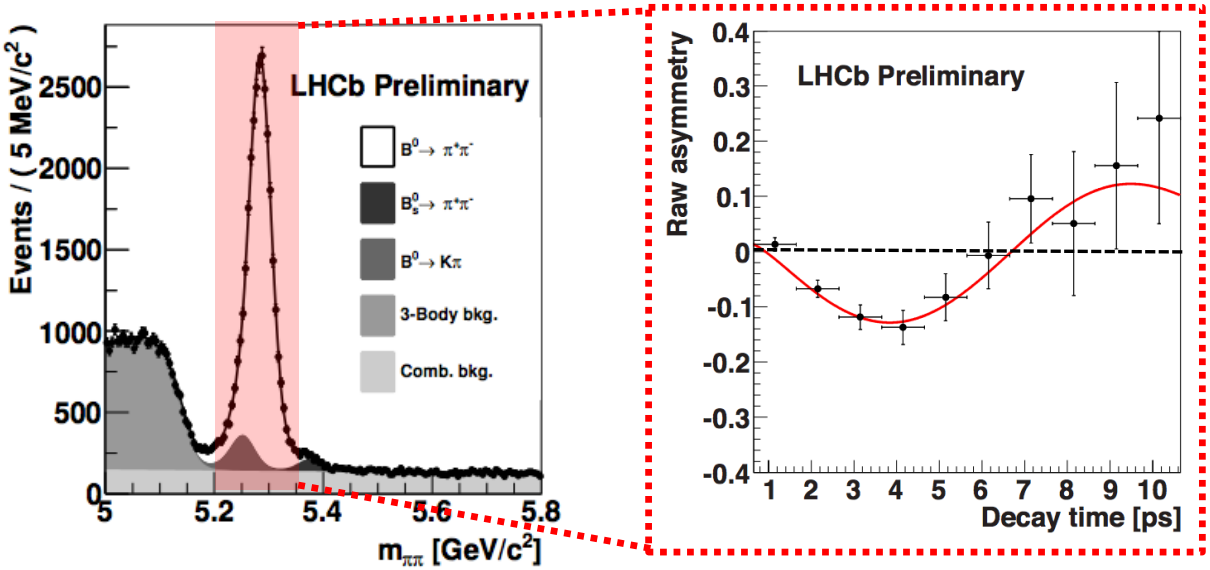
Mistag probability and decay time resolution dilute amplitude of time dependent asymmetries

- Use opposite side taggers calibrated using $B^0 \to K^+\pi^-$
- Determine per-event decay time resolution from decay time error computed in reconstruction calibrated with $B^0 \to K^+\pi^-$ and $B_s^0 \to D_s^+\pi^+$

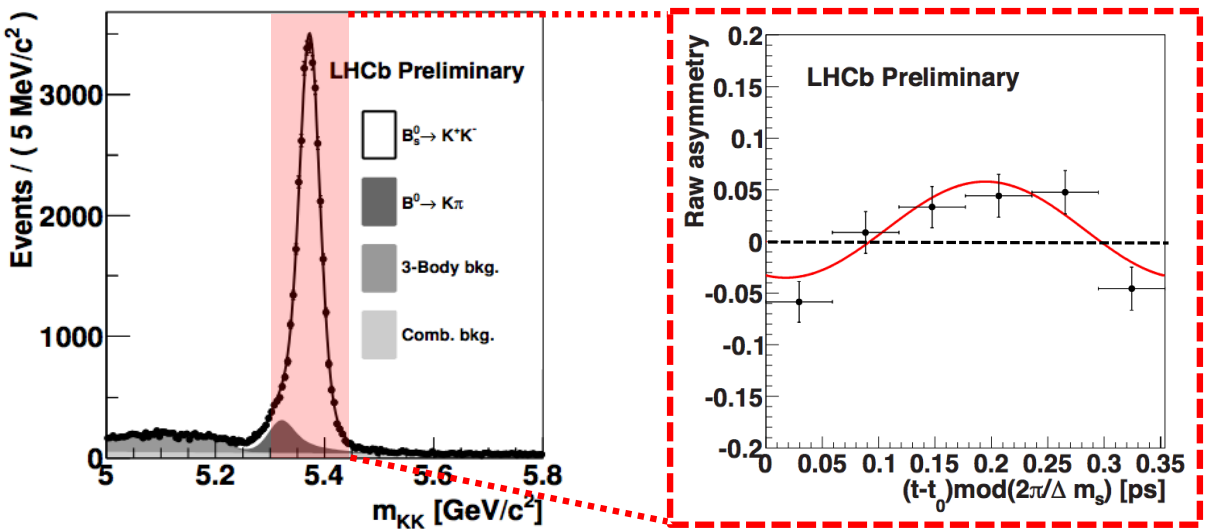


Results

[LHCb-CONF-2016-018]



$$C_{\pi^+\pi^-} = -0.24 \pm 0.07 \pm 0.01$$
$$S_{\pi^+\pi^-} = -0.68 \pm 0.06 \pm 0.01$$



$$C_{K^+K^-} = 0.24 \pm 0.06 \pm 0.02$$
$$S_{K^+K^-} = 0.22 \pm 0.06 \pm 0.02$$
$$A^{\Delta\Gamma}_{K^+K^-} = -0.75 \pm 0.07 \pm 0.11$$

val $\pm$ *stat* $\pm$ *syst*

Results

[LHCb-CONF-2016-018]

- Results in agreement with [JHEP 10 (2013) 183] and approximately twice more precise
- Naive CPV significance (neglect correlations and sum in quadrature)
  - $(C_{K^+K^-}, S_{K^+K^-}, A^{\Delta\Gamma}_{K^+K^-})$ is 4.7σ from $(0, 0, 1)$
  - $(C_{K^+K^-}, S_{K^+K^-})$ is 4.6σ from $(0, 0)$
  - $C_{K^+K^-}$ and $S_{K^+K^-}$ are 3.6σ and 3.3σ from 0 respectively
- First evidence of CPV in $B^0_s \to K^+K^-$ decay
- Best measurement of $S_{\pi^+\pi^-}$ from a single experiment
- Update also with same sign taggers will follow soon

Evidence for CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

[Nat. Phys. (2017)]

Motivations

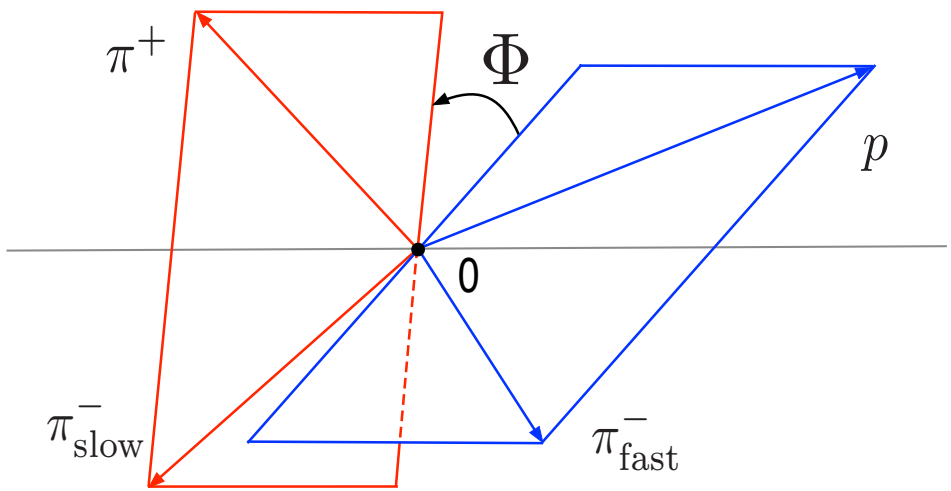
[Nat. Phys. (2017)]

- CPV predicted by SM in baryons but not observed yet
- In $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ tree and penguin diagrams have similar amplitude
- Local CPV in multibody decays can be larger that global CPV
- Possible to use $\hat{T}$-odd observables (triple products)

$$C_{\hat{T}} = \vec{p}_p \cdot \left(\vec{p}_{\pi^-_{\text{fast}}} \times \vec{p}_{\pi^+}\right) \propto sin\Phi$$

$$\mathcal{A}_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

$$\overline{\mathcal{A}}_{\hat{T}} = \frac{N(-\overline{C}_{\hat{T}} > 0) - N(-\overline{C}_{\hat{T}} < 0)}{N(-\overline{C}_{\hat{T}} > 0) + N(-\overline{C}_{\hat{T}} < 0)}$$



CP-violating observable

$$a_{CP}^{\hat{T}-\text{odd}} = \frac{1}{2}\left(\mathcal{A}_{\hat{T}} - \overline{\mathcal{A}}_{\hat{T}}\right)$$

P-violating observable

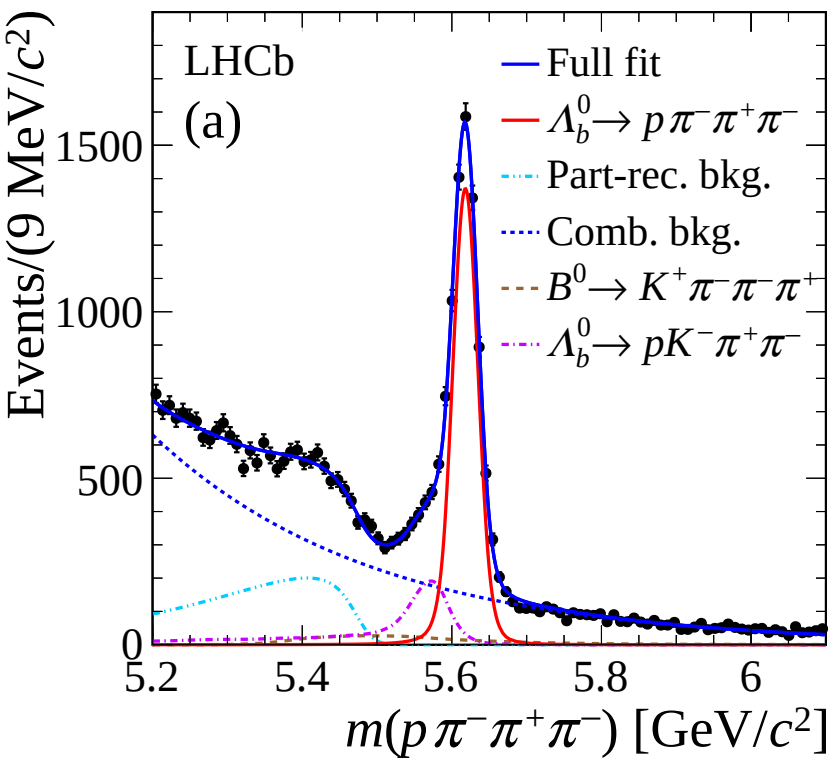
$$a_{P}^{\hat{T}-\text{odd}} = \frac{1}{2}\left(\mathcal{A}_{\hat{T}} + \overline{\mathcal{A}}_{\hat{T}}\right)$$

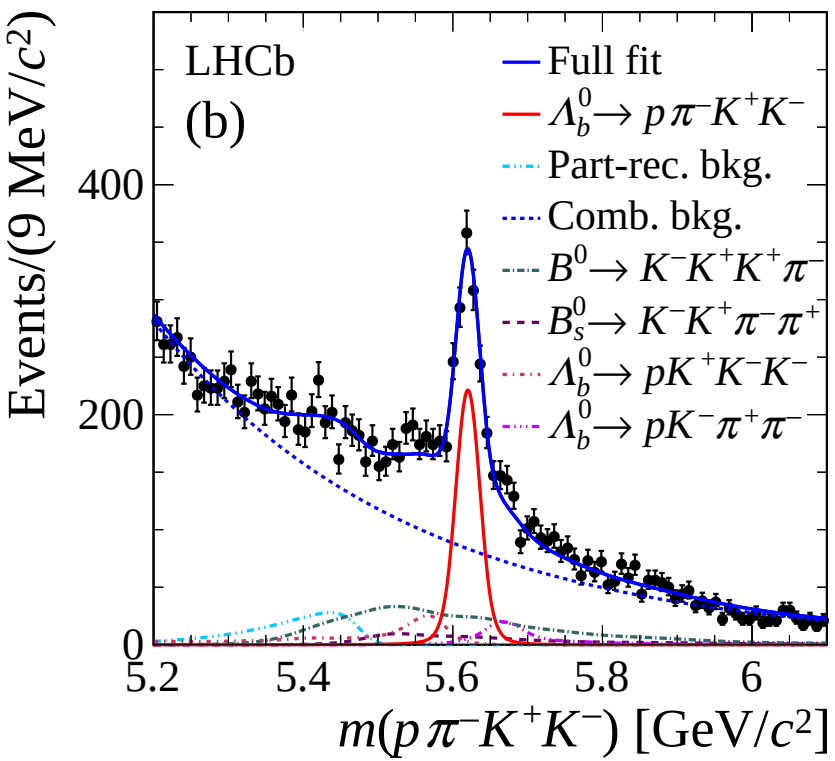
Analysis strategy

[Nat. Phys. (2017)]

- Search for CPV in $\Lambda_b^0 \to p\pi^- h^+ h'^-$ ($h^{(\prime)} = K$ or π) using triple products
- Use $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$ where no CPV is expected as control mode
- Simultaneous fit to $m(p\pi^- h^+ h'^-)$

$\mathcal{N}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = 6646 \pm 105$ (stat) $\mathcal{N}(\Lambda_b^0 \to p\pi^- K^+ K^-) = 1030 \pm 56$ (stat)

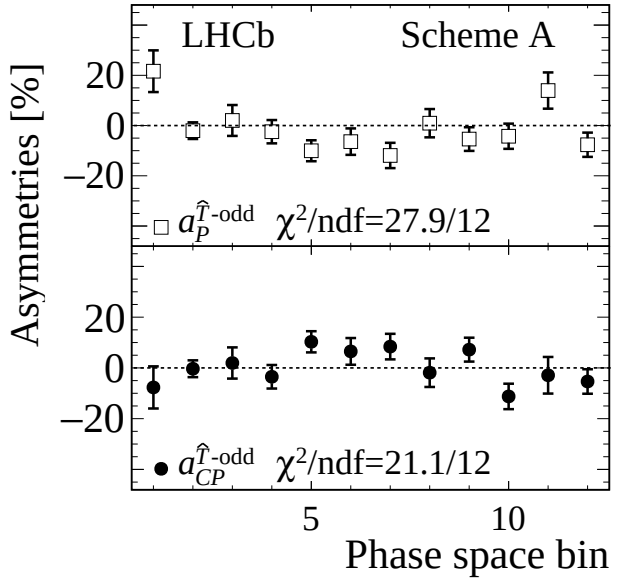


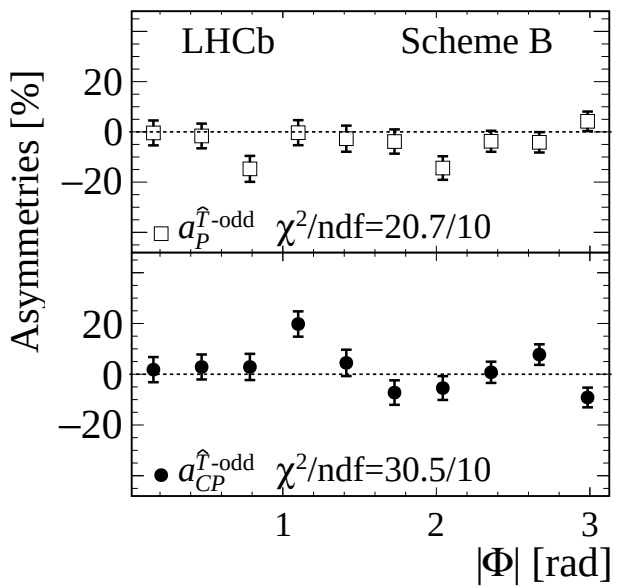


CPV measurement

[Nat. Phys. (2017)]

- Global CPV: Results compatible with P and CP conservation conservation
- Local CPV $\Lambda_b^0 \to p\pi^- K^+ K^-$: Limited yield divide only in two bins in $m(pK^-)$. Compatible with P and CP conservation
- Local CPV $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$: Use two different binning schemes:
  - Scheme A: 12 regions dominated by 2-body resonances ($\rho^0(770)$, Δ^{++}, N^*)
  - Scheme B: 10 uniform bins in Φ
  - P symmetry compatible at 2.2σ
  - 3.3σ evidence for CPV found combining both schemes





Rare *B* decays

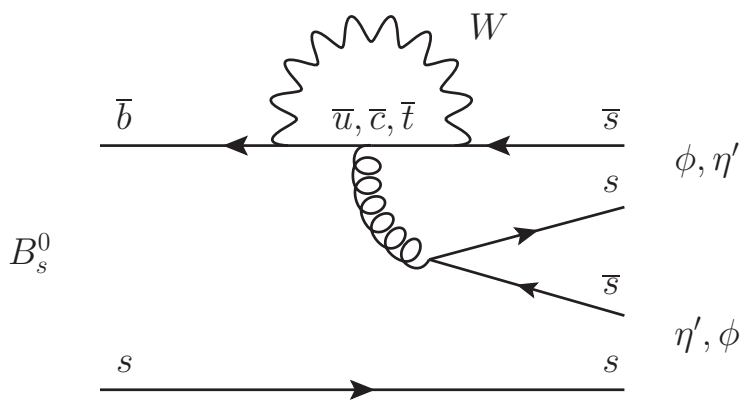
Search for the $B_s^0 \to \eta' \phi$ decay

[arXiv:1612.08110, Submitted to JHEP]

Motivations

[arXiv:1612.08110, Submitted to JHEP]

- Proceeds via $b \to s\bar{s}s$ penguin transition like $B_s^0 \to \phi\phi$ and $B_s^0 \to \eta'\eta'$
- Predictions cover wide range and have big uncertainties due to limited knowledge on form factors, penguin contributions, ω–ϕ mixing angle and s-quark mass



Theory approach	Yield $\mathcal{B}/10^{-6}$	Reference
QCD factorisation	$0.05^{+1.18}_{-0.19}$	[Nucl.Phys. B 675 (2003) 333-415]
QCD factorisation	$2.2^{+9.4}_{-3.1}$	[arXiv:hep-ph/0701146]
Perturbative QCD	$0.19^{+0.20}_{-0.13}$	[Phys.Rev. D 76 (2007) 074018]
Perturbative QCD	$20.0^{+16.3}_{-9.1}$	[Phys.Rev. D 80 (2009) 114026]
SCET	$4.3^{+5.2}_{-3.6}$	[Phys.Rev. D 78 (2008) 034011]
SU(3) flav. symm.	5.5 ± 1.8	[Phys.Rev.D 91 (2014) 014011]
FAT	13.0 ± 1.6	[arXiv:1608.02819]

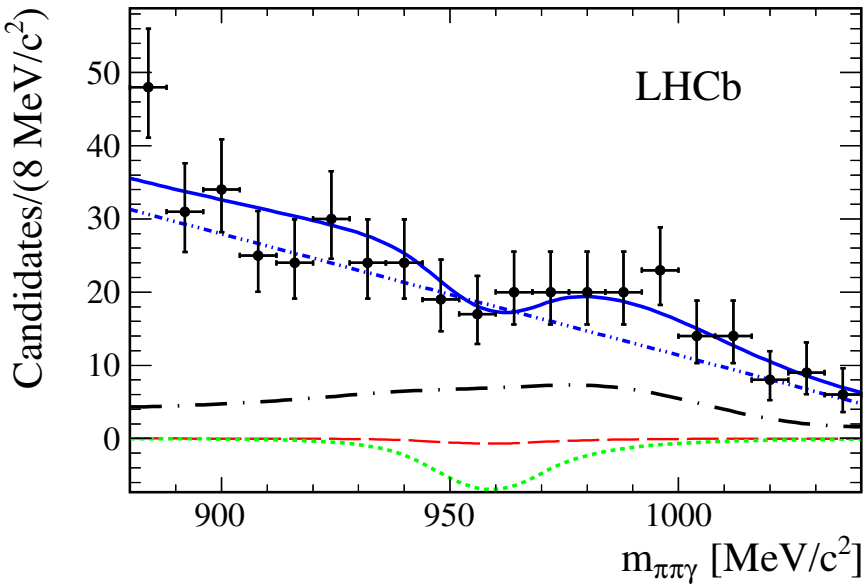
Analysis strategy

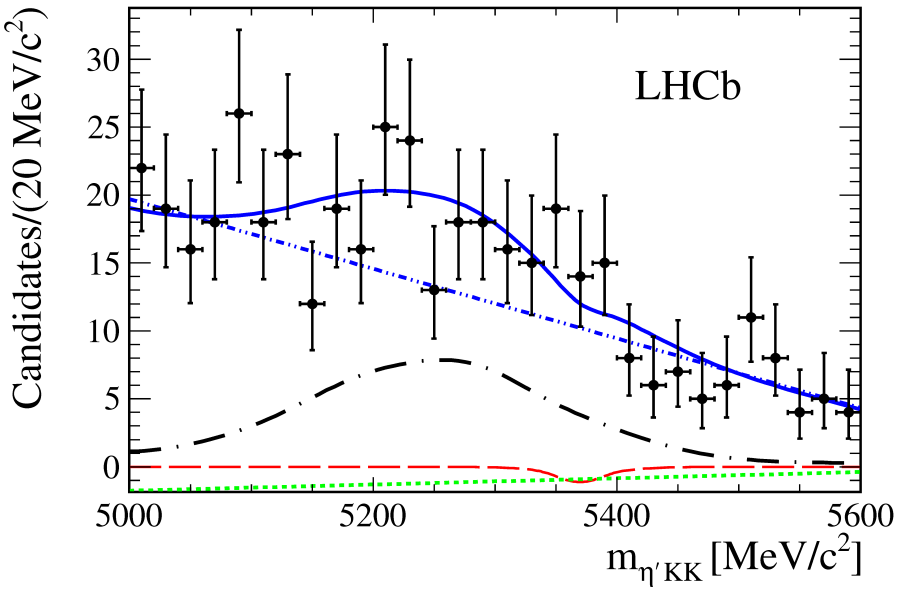
[arXiv:1612.08110, Submitted to JHEP]

- Signal: $B_s^0 \to \eta' \phi$
- Normalisation mode: $B^+ \to \eta' K^+$ ($\mathcal{B} = (70.6 \pm 2.5) \times 10^{-6}$)
- Reconstruct η' candidates as $\eta' \to \pi^+\pi^-\gamma$
- Dataset: LHCb Run I dataset (3 fb^{-1})
- Blinded until selection strategy finalised
- Fit: 2D ($m(\eta' K^+ K^-)$, $m(\pi^+\pi^-\gamma)$) and simultaneous for signal and normalisation mode
- Sensitivity: expected $> 5\sigma$ (40 events) for $\mathcal{B} = 4 \times 10^{-6}$

Results

[arXiv:1612.08110, Submitted to JHEP]





signal $B_s^0 \to \phi\phi(\pi^+\pi^-\pi^0)$ combinatorial comb. with real η'

- No indication of the signal ($\mathcal{N}(B_s^0 \to \eta'\phi) = -3.2^{+5.0}_{-3.8}$)
- Set upper limit on branching fraction

$$\mathcal{B}(B_s^0 \to \eta'\phi) < 0.82(1.01) \times 10^{-6} \quad \text{at } 90\%\,(95\%)\ \text{CL}$$

- Most central values of theoretical predictions significantly larger

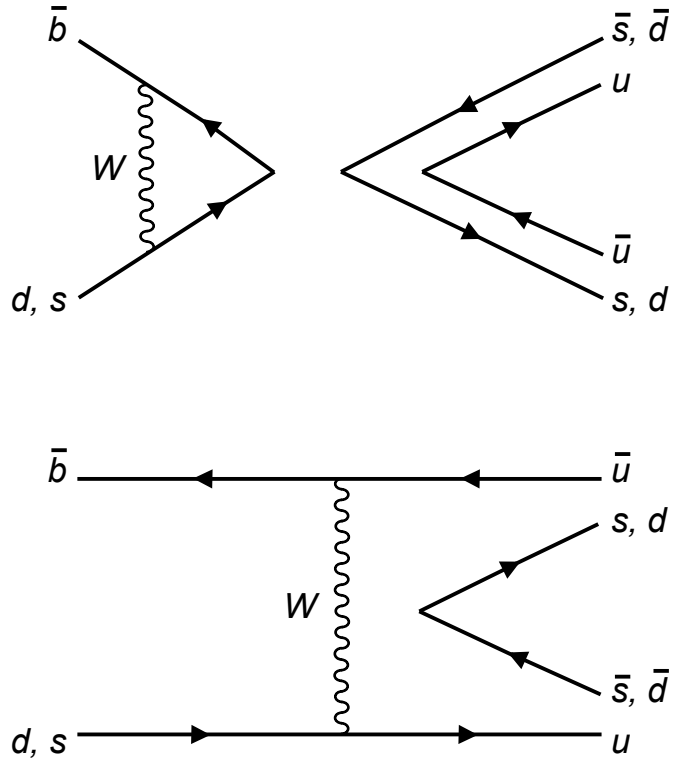
Observation of the $B^0 \to K^+K^-$ decay

[Phys. Rev. Lett. 118 (2017) 081801]

Motivations

[Phys. Rev. Lett. 118 (2017) 081801]

- $B^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$ proceed via weak annihilation transitions (all final state quarks different from initial state)
- Highly suppressed but possible enhancement from rescattering effects
- $B^0 \to K^+K^-$ unobserved so far, $B_s^0 \to \pi^+\pi^-$ observed in [JHEP 1210 (2012) 037]
- Precise BF measurement for the two modes provides input to improve knowledge of QCD dynamics in $B^0_{(s)} \to h^+h'^-$



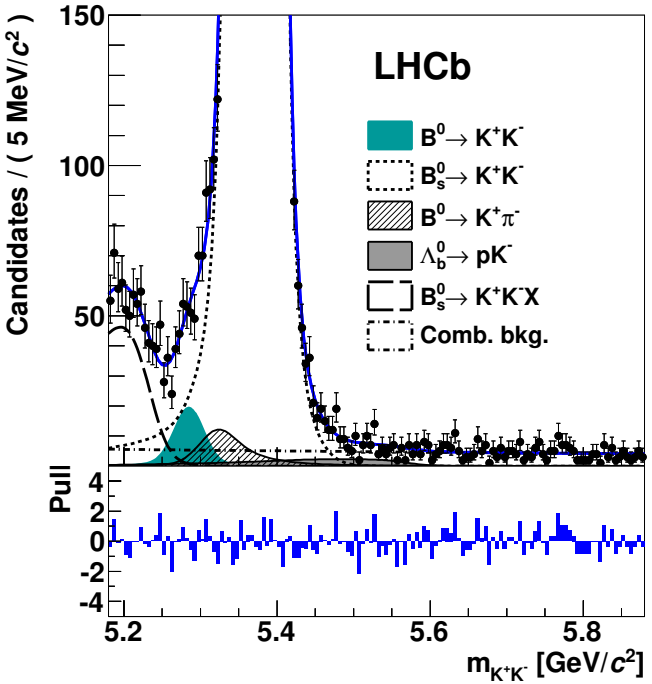
Analysis strategy

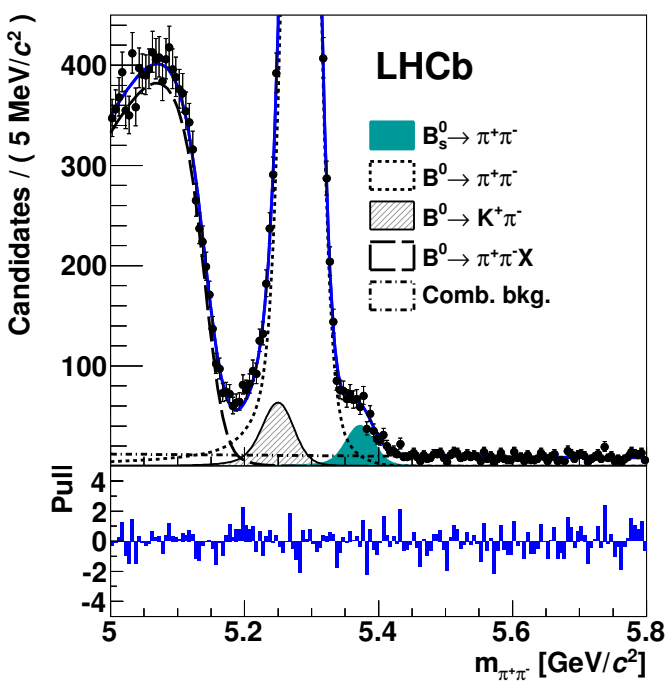
[Phys. Rev. Lett. 118 (2017) 081801]

- Signal: $B^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$
- Normalisation mode: $B \to K^+\pi^-$
- Dataset: LHCb Run I dataset (3 fb^{-1})
- Blinded until selection strategy finalised
- Selection: BDT against combinatorial background, particle identification criteria on charged hadrons
- Fit: Simultaneous fit to 2-body invariant mass of several mutually exclusive subsamples ($K^+\pi^-$, pK^-, $p\pi^-$, $\pi^+\pi^-$ and K^+K^-)

Results

[Phys. Rev. Lett. 118 (2017) 081801]





$B^0 \to K^+K^-$ observed at 5.8σ

Measured BF (World's most precise)

$$\mathcal{B}(B^0 \to K^+K^-) = [7.80 \pm 1.27(\text{stat}) \pm 0.81(\text{syst}) \pm 0.21(\mathcal{B}_{\text{norm}})] \times 10^{-8}$$

$$\mathcal{B}(B_s^0 \to \pi^+\pi^-) = [6.91 \pm 0.54(\text{stat}) \pm 0.63(\text{syst}) \pm 0.19(\mathcal{B}_{\text{norm}}) \pm 0.40(f_s/f_d)] \times 10^{-7}$$

- In agreement within uncertainties with pQCD [Phys. Rev. D 85 (2012) 094003]
- Agreement for $\mathcal{B}(B^0 \to K^+K^-)$ but significantly larger $\mathcal{B}(B_s^0 \to \pi^+\pi^-)$ than QCDF [Phys. Rev. D 80 (2009) 114026]

Conclusion

Presented several recent results from the LHCb collaboration:

- First observation of baryonic B_s decay
- First observation of 3 new $B^0_{(s)} \to p\bar{p}h^+h'^-$ modes and evidence of a fourth one New!
- First evidence of CPV in $B^0_s \to K^+K^-$ (with naive treatment of errors)
- First evidence of CPV in baryons
- World's best limit on $B^0_s \to \eta'\phi$
- First observation of $B^0 \to K^+K^-$ rarest hadronic B decay ever observed!

BACKUP

LHCb

[Int. J. Mod. Phys. A 30 (2015) 1530022]

Acceptance: $2 < \eta < 5$
$\sim 1/4$ of produced $b\bar{b}$ pairs.

Decay time resolution $\sim$ 45 fs

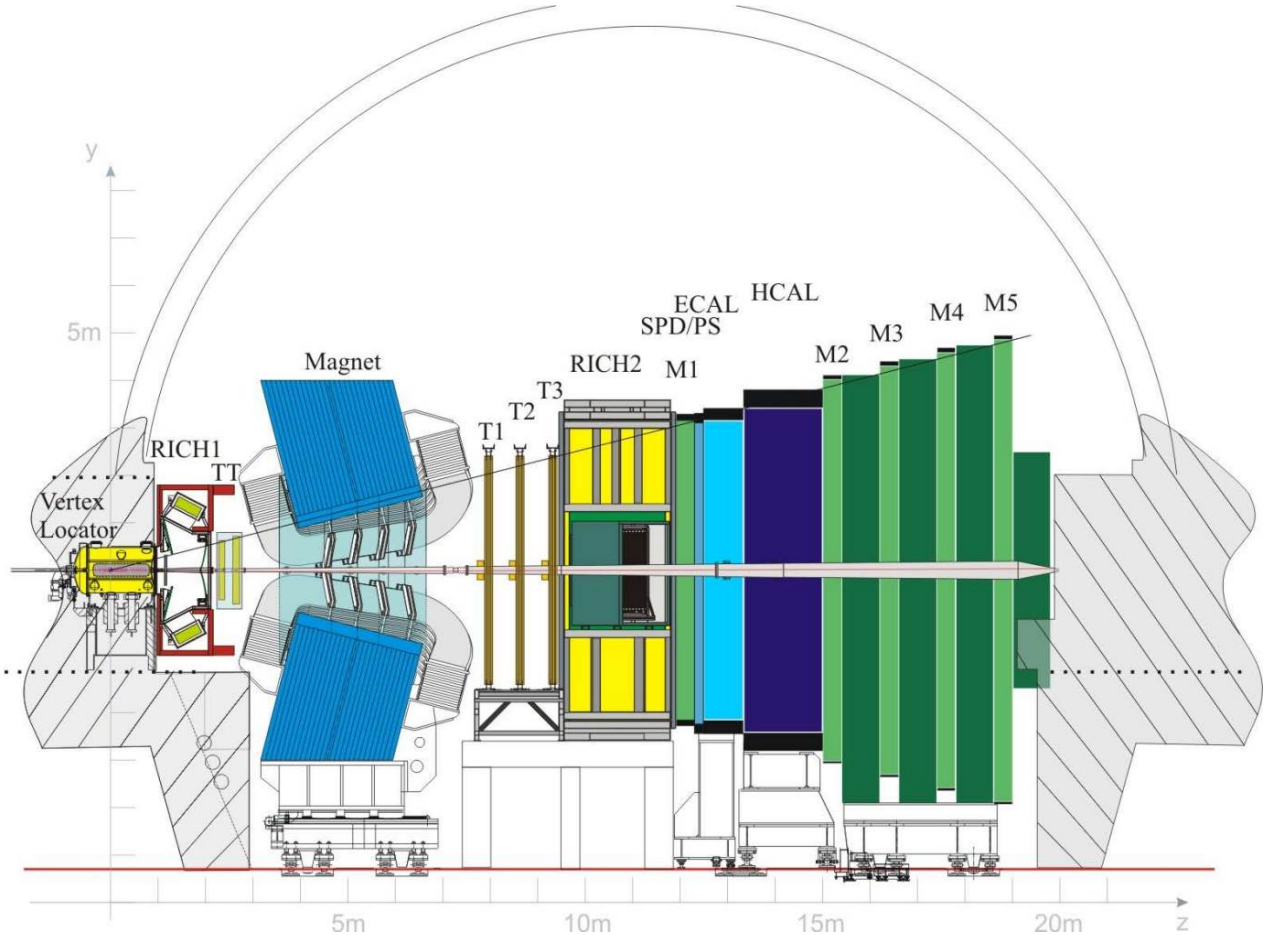
IP resolution $\sim 20 \mu m$

Vertex resolution $\sim$ 13 μm in x y (25 tracks)

$\Delta p/p \sim 0.5 - 1.0\%$

$\varepsilon(\mu) \sim 97\%$,
$misID(\pi \to \mu) \sim 1 - 3\%$

$\varepsilon(K) \sim 95\%$,
$misID(\pi \to K) \sim 5\%$



Reconstructing Λ and K^0_S [Int. J. Mod. Phys. A 30 (2015) 1530022]